MODEL FOLLOWING CONTROL FOR MD500 HELICOPTER

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Abstract

This paper describes the design results of a helicopter attitude control law based on the Model Following Control(MFC) method. The attitude controller is developed using a model appropriate for an unmanned helicopter, a dynamic inverse model that generates feed-forward MFC commands, and an error compensator with a PID to reduce the effects of model error. A de-coupling logic is designed to reduce the orders of inverse models separately. All components of the MFC is based on a linear helicopter model, including actuators, to represent a generic MD500 helicopter. The simulation results indicate that the attitude controller accurately follows the command model for multi-axis commands without the need for fine tuning of control gains. This study will be use for the base of MD500 helicopter unmanned technology.

1 General Introduction

1.1 Motive & objective of research

Recently, size of market for unmanned Air Vehicle has been increased rapidly. In the meantime, the interest of DRONE and unmanned helicopter has been increased also. The helicopters can vertical take-off and landing which can't do fixed-wing airplane. With these flying capabilities, helicopter has been received constant attention and place in private and military while developing the technology. However, the helicopter has a complex dynamics mechanism such as rotating rotor dynamics, so it is unstable than fixed-wing UAV(Unmanned Air Vehicle). To solve this disadvantage, currently unmanned helicopter technology has been more needed. Through continuous research, it is currently being carried out high-level modeling and design. In Koreanair research & development center, flight control systems and Software for manned helicopter to unmanned helicopter is now developing. The main purpose of the development of unmanned helicopter is not only military mission but also pesticide and rescue operations. This is because, it can alleviate the worry of accidents caused by the emergency of the unstable flight dynamic motion. For these reasons, unmanned helicopter has been developed from various fields for many reasons and purpose.

By characteristics of helicopter, in the disturbance situation, it is hard to recover to normal state with pilot's control. So, deduce a precise model through dynamic characteristics analysis is important and together, design a stable controller is very important too. But, classical control theory, such as PID(Proportional Integral Derivative) control, has some limitation that it is hard to design when it have unstable dynamics. In addition, we usually use linearization model to design a controller, it is very different to describe non-linear dynamic characteristics. In this paper, to solve a helicopter dynamics instability, we design a MFC controller as a robust controller to analyze the features and strength.

Model following control (MFC) was developed in early 1980's at NASA (National Aeronautics and Space Administration) by ADOCS (Advanced Digital Optical Control System) program. MFC theory is a modified method of internal model control (IMC). MFC has a robustness of model uncertainty and command tracking performance. The model following control can be designed a controller to follow the dynamic characteristics of the designed system. So the system that user want to control can follow the dynamic characteristics of the modeled system with model following controller. For the equivalent control input, comparing the output of the target system and modeled system is essential. If an error occurs, it has a structure which has a feedback signal of multiplied appropriate gain and error to the target system. Therefore, if model is exactly the same as real system, model following control in steady state will not corrupt the system. But, if the output of the actual system is subject to the output of the model because of the disturbance, model following control make the actual output of the system to follow the output of the model. It shows characteristics of model following control.

1.2 Configuration of paper

In section 2.1 of this paper include about helicopter control law. In section 2.2 contain the model following control technique applied in this study. On part 3, it has been described to include the result of simulation for analysis of designed controller. In section 3.1, description of the MD500 model used in this paper is written and finally section to analyze the simulation result in section 3.2 with conclusion.

2 Helicopter Control Law

2.1 Model following control design

Almost existing manned helicopter control is using rate response as a control input which is following angular velocity or heave velocity. But, in the case of unmanned helicopter, autopilot is mainly used and it also designed as a attitude command attitude hold (ACAH) mode. In this paper, a model with respect to yaw axis to follow the ACAH command to analyze the response about the pitch, roll and rate command.

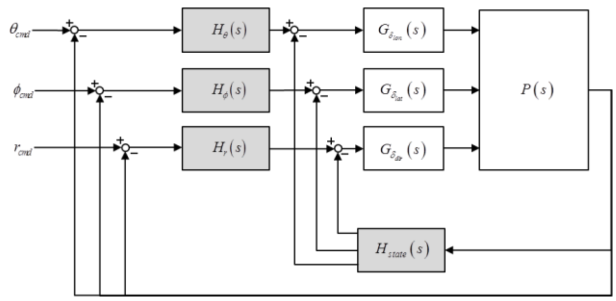

Fig. 1. PID control system

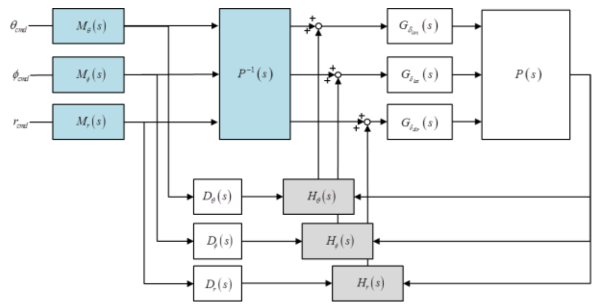

Fig. 2. Model Following Control(MFC) system

Fig. 1 and Fig.2 are PID control system and Model Following Control system. As you can see from the figure, unlike PID system, model following control system contained inverse model, command model and delay model to compensation for actuator model. With this structure, after comparison the output of the command model and actual model for the same control input, plant is constructed to follow the output of command model.

2.2 Command model design

Command model used in the model following control system is mainly represented by the roll and pitch attitude. In this paper, use a second order transfer function as a pitch / roll axis command model and use first order transfer function as a yaw / heave axis command model. Command model block diagram can be represented as shown below.

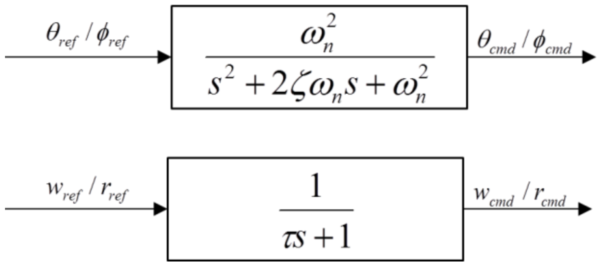

Fig. 3. Command model
(up: pitch/roll, down: yaw / heave)

Damping ratio(ξ) and natural frequency(ω) in the fig. 3 is variable for determining a attitude angle of the response characteristics against command input. The damping ratio is 0.7, it is for normal use and natural frequency is 2 rad/sec used to satisfy the level 1 bandwidth requirement of the ADS-33E. Other item are used with reference [3].

2.3 Inverse model design

Inverse model is a very important model that plays a key role in the model following control system structure. Inverse model is implemented as a helicopter inverse model and generating a feed forward control output for the command model. But, still difficult to inverse transform the usual high-order model. Even if inverse transform, they are difficult to implement in real drawback is equipped with the system. Therefore, most of the applications use the inverse effect of simplifying the model around the big variable. In this study, to be included in the inversion model, model following control can be derived from a linear motion model of the helicopter angular velocity.

$$\dot{q} = M_q q + M_u u + M_{\delta_{lon}} u_{lon} \qquad (1)$$

$$\dot{p} = L_p p + L_v v + L_{\delta_{lat}} u_{lat} \qquad (2)$$

$$\dot{r} = N_r r + N_{\delta_{ped}} u_{ped} \qquad (3)$$

The above formula (1-3) represents a SISO Decoupled (single input single output) dynamic model for the angular velocity. Calculate the inverse model from the equation (1-3) can be expressed as follows.

$$u_{lon} = \frac{(\dot{q} - M_q - M_u u)}{M_{\delta_{lon}}} = \frac{\left(\dot{q} - M_q q - \frac{M_u g}{s - X_u}\theta\right)}{M_{u_{lon}}} \qquad (4)$$

$$u_{lat} = \frac{(\dot{p} - L_p p - L_v v)}{L_{\delta_{lat}}} = \frac{\left(\dot{p} - L_p p - \frac{L_v g}{s - Y_v}\phi\right)}{L_{u_{lat}}} \qquad (5)$$

$$u_{ped} = \frac{(\dot{r} - N_r r)}{N_{\delta_{ped}}} \qquad (6)$$

Command model and inverse model used for the simulations in this paper is ultimately the same as Fig.4. [2]

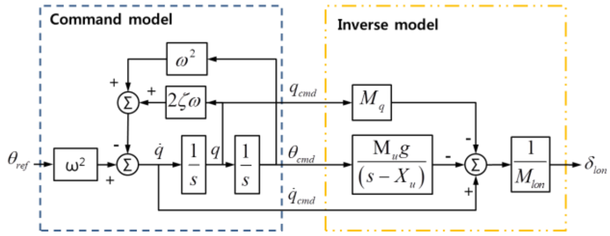

Fig. 4. Command and inverse model for pitch

2.4 Error compensator design

If the inverse model and the actual aircraft model is equivalent, control responses follow the command model output completely by the model following control structure. However, in the real world actual system, there are many errors such as disturbances, model error and system influence error. So it is necessary to constantly feedback compensator for the output of the command model and the error in the output of measured from the sensor of the actual system.

Error compensator has been designed to PID controller structure. In a real classic controller structure it is important that the performance of PID controller itself and the schedule that changes depending on the design point which is including airspeed and altitude are common. However, in case of the model following control, most of the scheduling role performed by inverse model. So, in general, the error compensator has the advantage of scheduling for separate design points.

$$u_{col} = k_w \tilde{w} + k_{iw} \int \tilde{w} \quad (7)$$

$$u_{lon} = k_\theta \tilde{\theta} + k_{i\theta} \int \tilde{\theta} + k_q \tilde{q} \quad (8)$$

$$u_{ped} = k_\phi \tilde{\phi} + k_{i\phi} \int \tilde{\phi} + k_q \tilde{p} \quad (9)$$

$$u_{ped} = k_r \tilde{r} + k_{ir} \int \tilde{r} \quad (10)$$

2.5 De-coupling logic design

In the model following control, it is common that designing the inverse model without considering a coupling between axis first and add a de-coupler to the controller output to solve a axis-to-axis coupling [2].

For a helicopter, the implementation of the system model with 4-axis dynamics (roll, pitch, yaw and heave), can be expressed as below:

$$y = Ax + Bu \quad (11)$$

Than here,

$$A = \begin{bmatrix} Z_u & Z_w & Z_q & Z_v & Z_p & Z_r \\ M_u & M_u & M_q & M_v & M_p & M_r \\ L'_u & L'_w & L'_q & L'_v & L'_p & L'_r \\ N'_u & N'_w & N'_q & N'_v & N'_p & N'_r \end{bmatrix}$$

$$B = \begin{bmatrix} Z_{u_{col}} & Z_{u_{lon}} & Z_{u_{lat}} & Z_{u_{ped}} \\ M_{u_{col}} & M_{u_{lon}} & M_{u_{lat}} & M_{u_{ped}} \\ L'_{u_{col}} & L'_{u_{lon}} & L'_{u_{lat}} & L'_{u_{ped}} \\ N'_{u_{col}} & N'_{u_{lon}} & N'_{u_{lat}} & N'_{u_{ped}} \end{bmatrix}$$

Above equation, system matrix and the input matrix can be separated as terms of directly connected to each axis (A_0, B_0, u_0) and axis-to-axis coupling term ($\tilde{A}, \tilde{B}, \tilde{u}$).

$$\begin{aligned} A &= A_0 + \tilde{A} \\ B &= B_0 + \tilde{B} \\ u &= u_0 + \tilde{u} \end{aligned} \quad (12)$$

Than here,

$$\tilde{u} = -B_0^{-1}\left(\tilde{A}x + \tilde{B}u_0\right) \quad (13)$$

Summarizing the above equation (13) with equation (11)

$$\begin{aligned} y &= Ax + Bu \\ &= Ax + B\left(u_0 - B_0^{-1}\left(\tilde{A}x + \tilde{B}u_0\right)\right) \\ &= Ax + Bu_0 - BB_0^{-1}\left(\tilde{A}x + \tilde{B}u_0\right) \end{aligned} \quad (14)$$

Therefore, the term includes the decoupling equation (13) and (11) becomes the same order when BB_0^{-1} is identity matrix. At this time you can completely eliminate the coupling effect.

$$BB_0^{-1} \approx I \quad (15)$$

In summary matrix of equation (11) and the equation (12) by substituting in the equation (15) can be determined the de-coupler of the final system, as follows:

$$BB_0^{-1} = \begin{bmatrix} 1 & \frac{Z_{u_{lon}}}{Z_{u_{col}}} & \frac{Z_{u_{lat}}}{Z_{u_{col}}} & \frac{Z_{u_{ped}}}{Z_{u_{col}}} \\ \frac{M_{u_{col}}}{M_{u_{lon}}} & 1 & \frac{M_{u_{lat}}}{M_{u_{lon}}} & \frac{M_{u_{ped}}}{M_{u_{lon}}} \\ \frac{L'_{u_{col}}}{L'_{u_{lat}}} & \frac{L'_{u_{lon}}}{L'_{u_{lat}}} & 1 & \frac{L'_{u_{ped}}}{L'_{u_{lat}}} \\ \frac{N'_{u_{col}}}{N'_{u_{ped}}} & \frac{N'_{u_{lon}}}{N'_{u_{ped}}} & \frac{N'_{u_{lat}}}{N'_{u_{ped}}} & 1 \end{bmatrix} \approx I \quad (16)$$

3 Simulation and analysis

3.1 MD500 helicopter

In this study, the controller performance was analyzed through a simulation using a MD500 model helicopter. Hughes MD500 began life in response to a U.S Army requirement for a light observation helicopter in 1960s. The 500 series design features shock-absorbing landing skid struts, a turboshaft engine mounted at a 45-degree angle toward the rear of the cabin pod, a fuel tank cell under the floor and the battery in the nose. The engine exhaust port is located at the end of the cabin pod underneath the tail boom. It has a short-diameter main rotor system and a short tail, giving it an agile control response and is less susceptible to weather-cocking. MD500 helicopter has a specification as follows:

Tabe. 1. MD500 helicopter specification

General characteristics	
Crew	1~2
Capacity	5 total
Length	9.4 m
Rotor diameter	8.03 m
Height	2.48 m
Empty weight	493 kg
MTOW	1,157 kg
Performance	
Maximum speed	152 knots
Cruise Speed	125 knots
Range	605 km
Service ceiling	4,875 m
Rate of climb	8.6 m/s

Fig. 5. MD500 configuration

Dynamical model of the helicopter refer to Helicopter Handling Qualities Data [4] of NASA. The linearization model used in the simulation analysis was derived from FlightLab S/W. In this study, we analyzed the result of design point at 60 knots.

3.2 Simulation result

Simulation model contained a linearization model, actuator model, inverse model, error compensator and time delay phase model. And it shows simulation result for a response to a double-let and pulse input command. In case of error compensator, as previously mentioned it is only compensate the model error, so effect of the control gain is relatively small. In this study the control gains was tuned through the simulation. However, it is necessary to optimize the control gains in order to satisfy the various control requirements such as Bandwidth, Damping ratio, Quickness and Margin, at the same time. The control gains used in the simulation was shown in Table. 2.

Table. 2. Error compensator PID gain (at 60knots)

Mode	Gains	Values
Heave	k_w	0.08
	k_{wi}	0.05
Pitch	k_θ	5
	$k_{\theta i}$	4
	k_q	1
Roll	k_ϕ	4
	$k_{\phi i}$	3
	k_p	1
Yaw Rate	k_r	2
	k_{ri}	1

Fig. 6 shows the results of each axis command – heave axis 2m/s step input, roll/pitch axis 5 degree double-let input, yaw angular velocity 2deg/s input.
Despite the current MD500 helicopter model include a coupling and actuator effect, it shows the model output is accurately following a command of all axes caused by model following controller and de-coupler.
In the case of heave axis is to generate some movement during pitch maneuver due to the cyclic and collective cross coupling effects, kinetic impact by effect of actuator, this is

expected to be solved through the improvement of the expansion of inverse model order and the modification of de-coupler model.

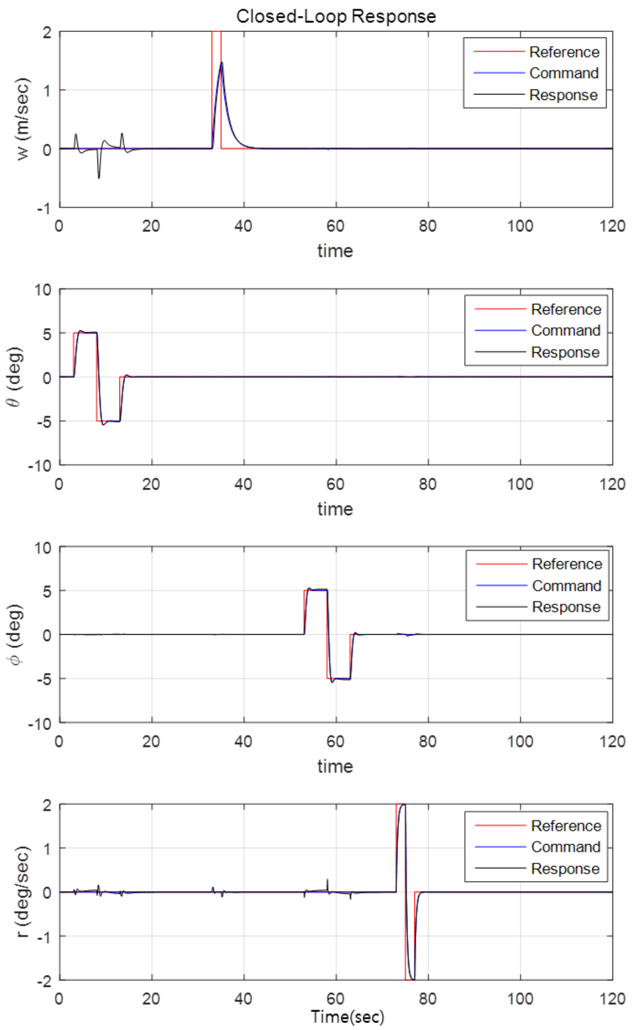

Fig. 6. Simulation result

4 Conclusion

Model following control (MFC) is a technique that utilizes an experimental modeling technique after identifying the exact model helicopter state, to obtain the information of handling and stability and requirement of the pilot at the same time. In this study, we designed the command model, inverse model and error compensator to meet the unmanned helicopter based on the MD500 helicopter and confirmed the control performance of model following control by simulation. On future work, Through the optimization of the control gains of error compensator, increase accuracy of the inverse model and nonlinear model simulations, it plans to improve the performance of the control law for the unmanned helicopter.

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